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A JOURNAL OF HIGHWAY RESEARCH

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Interstate Route 65 bypassing Lebanon, Ind.

IN THIS ISSUE:

Characteristics of passenger-car travel for highway user benefit studies.

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E. A. Stromberg, *Acting Editor*

IN THIS ISSUE

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Characteristics of Passenger-Car Travel on Toll Roads and Comparable Free Roads for Highway User Benefit Studies

*BY THE TRAFFIC OPERATIONS DIVISION
BUREAU OF PUBLIC ROADS*

Reported [1] by PAUL J. CLAFFEY
Highway Research Engineer [2]

Among the factors important to an accurate analysis of the benefits accruing to passenger-car users through highway improvements are the average overall rates of fuel consumption and speed by type of road, the effects of traffic impedances, the relative attractiveness of the different types of highway improvement benefits to motorists, and the value to motorists of time saving and increased driving comfort. Data useful to passenger-car benefit studies in connection with each of these factors were obtained in 1959 during the operation of a passenger vehicle on 8,000 miles of primary highways in 17 States. These data included rates of fuel consumption, overall speeds, speed changes identified by cause, and records of all traffic impedances.

The study route included 14 sections of toll route where drivers traveling between two particular points have a choice between use of a modern controlled-access toll route or an alternate free route of lesser design quality. At each of these comparison sections, vehicle data were collected for trips on both the toll and free routes. In addition, interview stations were operated on each of the alternate routes to obtain information from the drivers using them.

This report presents the findings of the study, including the average overall rates of fuel consumption and speed on major existing highways and on toll routes and the variation in these overall rates as affected by the frequency of driveways and cross roads, as well as the effects of traffic impedances on passenger-car operation. The report also shows the proportion of passenger-car users electing to use the toll route at each of the 14 toll route comparison sections, and the relative attractiveness to users of the types of benefit realized on both the toll routes and free routes. Finally, the data collected at the toll route comparison sections were subjected to a separate analysis to obtain estimates of the value to motorists of the time saving and increased driving comfort achieved through highway improvements.

Introduction

SOME OF THE FACTORS important to passenger-car benefit studies were investigated by the Bureau of Public Roads during the summer of 1959 by operating a passenger vehicle a distance of 14,000 miles on primary highways in 17 Eastern States and collecting, during this travel, a variety of data relative to passenger-car operation and highway travel characteristics. Included as portions of the study route were 14 locations where a toll road and a major free route are in a position to serve the same traffic. These were taken to represent controlled-access highways of modern design, in the case of the toll roads, and typical primary highways lacking control of access and some of the other important modern design features, in the case of the corresponding free routes. At each of the 14 locations several comparison runs were made on both the toll road and the free road. At the time of these test runs, interview stations were operated on each route to determine the relative use of the roads and to obtain trip purpose and driver preference data.

[1] Presented at the 40th annual meeting of the Highway Research Board, Washington, D.C., January 1961.
[2] Dr. Claffey is also Associate Professor of Civil Engineering, Catholic University, Washington, D.C.

Summary of Findings

Fuel consumption and speed

Several types of data useful in analyses of the benefits accruing to passenger-car users through highway improvement were developed in this study. Among these were average overall rates of fuel consumption and speed for operation on existing major 2-lane and 4-lane routes in both urban and rural areas and for operation on toll roads. These data showed that there was little difference between overall speeds on 2-lane roads and 4-lane roads except on main urban routes of large cities outside of the downtown areas where overall speeds on the 4-lane routes were approximately 25 percent greater than on the 2-lane routes. The greatest difference in average overall operating speed observed was between the 60.1 m.p.h. average on rural 4-lane divided controlled-access routes and the 48–50 m.p.h. average on 2- and 4-lane rural routes without control of access.

The fuel consumption rate on the rural 4-lane divided controlled-access routes was about 12 percent greater than on the rural routes without control of access which, in turn, was about 15 percent greater than on urban routes. These differences in fuel consumption rates reflect the over-riding effect of speed on rate of fuel consumption. For the typical traffic volumes carried by existing thoroughfares having no access control, there was little difference either in speeds or in fuel consumption rates for operation on 4-lane routes as compared to operation on 2-lane routes.

Traffic impedances

Certain of the effects of traffic signals, access points (driveways and cross roads without signal protection), and sharp curves on passenger-car operation, together with the average frequencies of these impedances on the 8,000 miles of major routes studied, are included in this report. The study vehicle was required to stop at 43 percent of the traffic lights encountered in urban areas and at 30 percent of those in rural areas. When stopped at traffic lights, there was an average stopped delay of 0.29 minute in urban areas and 0.21 minute in rural areas. Also, the study vehicle was slowed by other vehicles entering or leaving driveways at 1 in every 200 of the driveways encountered in urban areas and at 1 in every 125 of the driveways in rural areas. These data, together with data on speed changes and on the average frequencies of impedances, can be very useful in user benefit computations by providing a means of estimating the effects on traffic operations of highway improvements which

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eliminate individual impedances or groups of impedances.

Toll route comparison sections

The relative use of toll routes and alternate free routes by drivers familiar with both routes, and the reasons given by drivers on the compared routes for using either the toll route or the free route, serve to show the relative attractiveness to passenger-car users of the different types of benefits arising from highway improvements. The type of benefit most important to motorists was found to be time saving, with an average of 80 percent of the passenger-car drivers on toll roads and 21 percent of those on free roads stating they selected their travel route on the basis of time saving. The second most important reason given by passenger-car users for selecting their route was greater comfort and convenience. The highway benefits considered of least importance by passenger-car users in their selection of route were found to be greater safety and lower travel costs. Only 13 percent of the free road users indicated that they were influenced not to use the toll road because of the cost factor.

Monetary evaluations

Analysis of the data for comparative toll road and free road trips arrived at an estimate of the average passenger-car user's evaluation of time saving of 2.37 cents per minute of travel time saved, and an estimate of his evaluation of an improvement in driving conditions (measured in units of speed change reduction) of 0.048 cent per 1 m.p.h. reduction in speed change.

The estimate of the value of time saving was of a relatively high order of accuracy; but this was not so for the value of a speed change reduction, largely because there are presumably significant factors affecting driving comfort and convenience which are not reflected in speed changes. The value of each unit of speed change reduction, as computed in this study, is therefore somewhat high for general use as a measure of driving comfort benefit. However, it may be used to estimate driving comfort benefits arising from improvements which reduce the number of speed change units on roads similar to those for which the study data were obtained—primary rural roads without controlled access.

Finally, the study arrived at the following estimates of the comfort and convenience benefits that users receive through given highway improvements: Elimination of a traffic signal stop in rural areas, 4.32 cents; elimination of a sharp curve, 0.72 cent; elimination of a slowdown (for a through vehicle) at an access point, 0.96 cent.

Background for the Study

An accurate determination of the benefits accruing to passenger-car users through highway improvements of various kinds is of paramount importance in highway user benefit studies. The number of passenger cars on the roads and streets and the volume of passenger-car travel accumulated each year presumably make the aggregate benefits from highway improvement for this type of vehicle greater than the combined total for all other types of vehicles.

Among the important factors in passenger-car benefit studies are: (1) Fuel and time consumption both on thoroughfares having numerous traffic signals, access points, and sharp curves, and on divided highways with no traffic signals and fully controlled access, (2) the effect of traffic signals, access points, and curvature on highway vehicle operation, (3) the relative importance to motorists of the various types of benefit accruing through highway improvements, and (4) estimates of the value to the motorists of the time saving and increased driving comfort accruing to users through highway improvements. These items are concerned both with the overall effects of certain types of highway improvement on passenger-car operations and with the values drivers place on improved travel conditions. Numerous other factors having important effects on passenger-car user benefits, such as the relationship between highway design characteristics and accident rates, the effect of surface conditions and vehicle speeds on vehicle maintenance costs, and the value of reduced travel distance, are not included in this study.

Fuel and time consumption in passenger-car operation is affected by several highway factors, including length, relation of capacity to average daily traffic, the frequencies of sharp curves, intersections at grade, and driveway entrances, surface type, and gradients. Some data are currently available on the fuel and time consumption of passenger cars as affected by each of these factors, and several studies have been made of the overall fuel and time consumption of passenger cars operating over limited distances under a particular set of highway conditions (*1, 2*).[1] However, for benefit studies of large-scale improvement projects more information is needed on overall average speeds and average fuel-consumption rates for operation on typical present-day highways and on highways constructed to the highest design standards.

Predictions of the time and fuel benefits to arise through a general highway improvement program can be made by summing the savings for each item of improvement, such as elimination of intersections at grade and addition of traffic lanes. However, time and fuel savings computed in this manner should be compared with the difference in overall fuel and time consumption of highways of the general type as that involved in a particular analysis, and highways built to high standards, to guard against inadvertently inflating benefits by counting the same items of benefit more than once. Moreover, average overall values of time and fuel consumption for operation on roads which have intersections at grade, frequent access points, and sharp curves, and for operation on divided highways with full control of access, can often be used to make preliminary estimates of the fuel and time savings to result from a particular major highway improvement project.

[1] Italic numbers in parentheses represent references, page 176.

Traffic impedances such as traffic lights, access points, and sharp curves affect vehicle operation by forcing drivers to make undesired stops and slowdowns. These speed changes not only increase fuel and time consumption but are annoying to drivers. As an aid to estimating the extent of the benefits to accrue to motorists through highway improvements that eliminate these impedances, information should be available on the frequency of the different types of impedances, the average speed changes caused by each impedance, and, in the case of stops for traffic signals and stop signs, the average duration of the stopped delays.

An aspect of user benefit analysis of significance in connection with passenger-car benefit studies is the relative preference of users for the various types of benefit arising through highway improvement. Information on the relative attractiveness to motorists of reduced travel cost, time saving, greater safety, and increased driving comfort can be of material assistance in the computation of benefits by providing a guide to the kinds of improvement most desired by users and to the relative advantages, from the users' point of view, of the types of benefit realized from these improvements.

A knowledge of motorists' evaluation of two of the benefits brought about by highway improvements—time saving and increased driving comfort—is of paramount importance in passenger-car benefit studies. Many highway improvements, particularly those on a large scale in rural areas, bring about higher average operating speeds. Since for the normal range of passenger-car speeds in rural areas the operating costs for fuel, oil, and maintenance increase with increased speed, these improvements frequently result in increased operating costs (*3*). Consequently, most of the benefits accruing to passenger-car users through highway improvement are those associated with time saving, increased driving comfort, and safety. The benefits to users resulting from reductions in accident rates through road improvements are subject to continuing study and research. The monetary values to users of time saving and increased driving comfort have an importance in benefit analyses at least as great as accident cost saving, and warrant thorough investigation.

The Study Operation

The study vehicle

The vehicle used for the study was a 1959 six-cylinder, four-door, standard station wagon of popular make, equipped with automatic shift. It was necessary to use the station wagon rather than a sedan or other type of passenger car in order to provide sufficient interior space to carry the bulky equipment for recording study data. However, it is believed that the data collected are representative of passenger-car operation. Although the study vehicle was comparatively new and had been operated only 3,380 miles at the beginning of the study, it was placed on a dynamometer and its engine performance was

given a special check immediately preceding the beginning of the trip. All engine defects discovered at this time, however minor, were corrected. In the 2-month study period, during which the vehicle covered over 14,000 miles of travel, all recommendations of the manufacturer in regard to vehicle care and maintenance were strictly adhered to.

The gross weight of the vehicle when loaded with the data collecting equipment and carrying both the vehicle operator and the observer was 4,900 pounds. The frontal cross section of the vehicle itself was 6 feet wide by 5 feet high, the same as for a passenger car of the same make, but the total cross section was increased by an open-top wooden box affixed to the roof of the vehicle to support and protect a gasoline-powered generator, needed to provide electrical power to operate the data-collecting equipment located inside the station wagon. This box added 1½ feet to the vehicle height for almost the full width of its roof. The full cross section of the vehicle when equipped for collecting data was thus 6 feet wide by 6½ feet high.

Data-collecting equipment

The data-collecting equipment (described in detail in the following paragraphs) consisted of an electronic device for measuring distance and speed data, an automatic printer for recording distance, speed, and time data, a code box for manually adding code numbers to the printer record tape, a fuelmeter, and several hand counters.

The items of electronic equipment were interconnected as a unit called the "traffic impedance analyzer" (see fig. 1). The instrument for measuring distance and speed was actuated by a flexible cable connection to the cable of the vehicle's speedometer. The output information from this instrument was directed as a series of electrical impulses into the automatic printer through appropriate electrical connections. The printer recorded automatically at intervals of one second on a strip of paper tape, registering the travel distance to hundredths of a mile (from a fixed point, usually the beginning point of a study run), the vehicle speed to the nearest mile per hour, and the elapsed time in seconds since leaving the initial point of the study run.

A manual code box with 20 push buttons arranged in two columns of 10 buttons each enabled the observer to record any number from 0 through 9 in each of two columns of the printer tape, changing the numbers each second if necessary. A typical sample of the printer tape is shown in figure 2. A recent article in Public Roads contains a full description of the traffic impedance analyzer and an explanation of the operation of its component parts (*4*). However, at the time this study was made the automatically recording fuelmeter described in that article was not yet fully developed for use in the traffic impedance analyzer.

Vehicle fuel consumption data were obtained by using a bellows-type fuelmeter connected to the gasoline line of the vehicle between the fuel pump and the carburetor. The instrument was mounted on the right side of the front seat of the vehicle so as to be easily read by the observer who sat on the rear seat. The fuelmeter, which gave fuel consumption readings to the nearest one-sixtieth of a gallon, was read and the data recorded by the observer at each study check point (as described below under test procedure). Fuel consumption data so obtained were frequently checked for accuracy during the study by comparing the difference in fuel readings between successive additions to the fuel tank with the quantity of fuel put into the tank as measured by the gasoline station fuel pump.

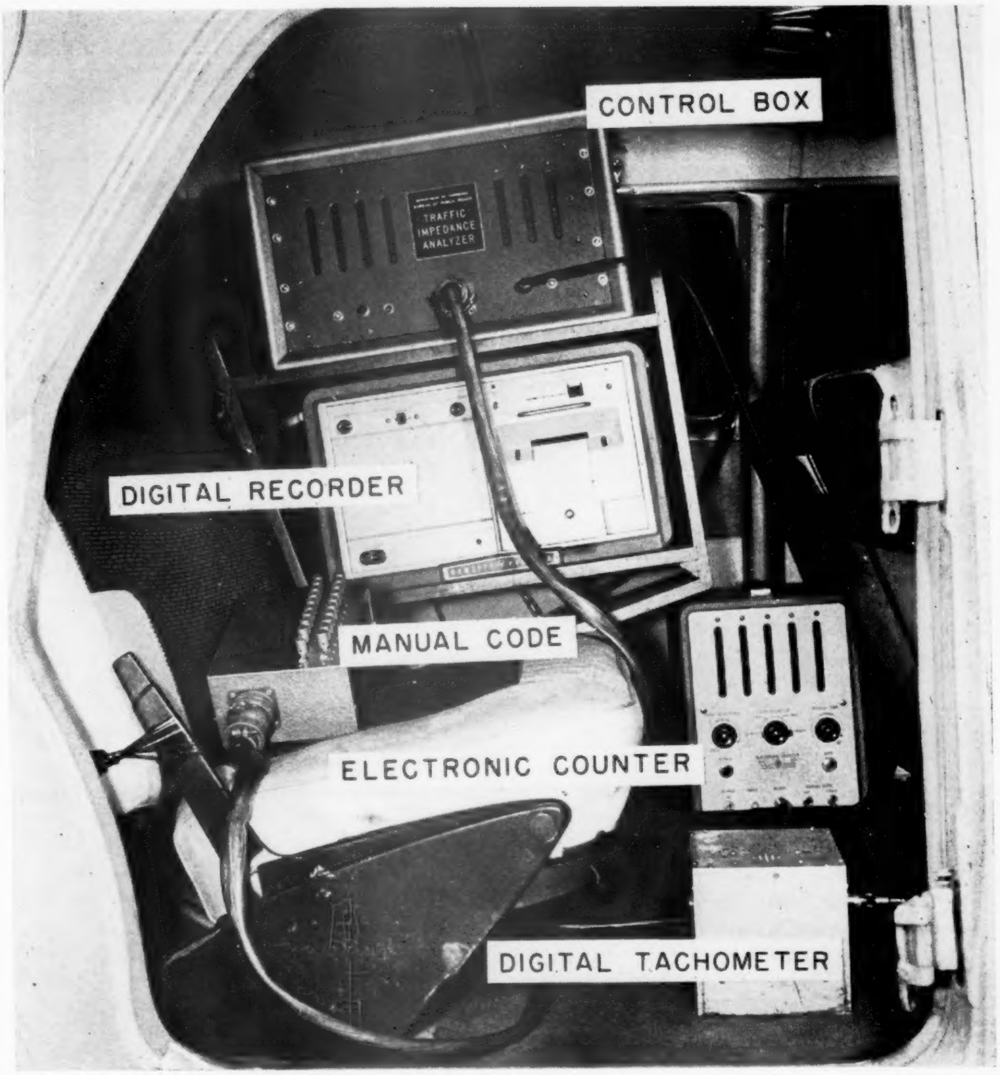

Figure 1.—The traffic impedance analyzer equipment, mounted on the rear seat of the study vehicle.

Study route

The 8,000-mile study route ran north from Washington, D.C., by way of Elizabeth, N.J., to Syracuse, N.Y.; thence east to Boston, Mass., and north to Portland, Maine. From Portland the route ran westward through Syracuse and Buffalo, N.Y., Toledo, Ohio, Elkhart, Ind., Springfield, Ill., and Hannibal, Mo., to Wichita, Kans. From Wichita the route ran south through Tulsa and Oklahoma City, Okla., to Fort Worth, Tex.; thence eastward through New Orleans, La., and along the Gulf coast to Tallahassee, Fla., and southward to West Palm Beach, Fla. From West Palm Beach the route ran northward through Daytona Beach and Jacksonville, Fla., Savannah, Ga., and Richmond, Va., to Washington, D.C. The termini of each of the free road sections of the study route, together with their route numbers, are listed in table 1 in the order in which the data were obtained. All toll road comparison sections are listed in table 2.

Operating procedure

On each section of the route for which data were collected, the study vehicle was operated from one end of the section to the other in a

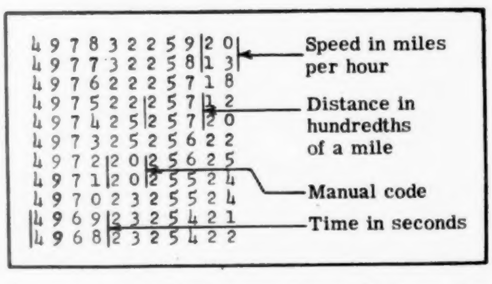

Figure 2.—Typical record sample from the traffic impedance analyzer.

Table 1.—Free road study sections [1]

No.	Initial point	End point	Route
30	Braman, Okla	Tulsa, Okla	U.S. 177, 77, 75
31	Oklahoma City, Okla	Oklahoma City, Okla.[2]	U.S. 77
32	Moore, Okla	Ardmore, Okla	U.S. 77
33	Fort Worth, Tex	Dallas, Tex	U.S. 80
34	Fort Worth, Tex	Dallas, Tex	Dallas-Fort Worth Tpk.
35	Dallas, Tex	Dallas, Tex.[3]	U.S. 80
36	Shreveport, La	Shreveport, La.[2]	U.S. 80, 71
37	Shreveport, La	Baton Rouge, La	U.S. 71, 190
38	Baton Rouge, La	Baton Rouge, La.[2]	U.S. 61
39	Gonzalez, La	New Orleans, La	U.S. 61
40	New Orleans, La	New Orleans, La.[4]	U.S. 90
41	New Orleans, La	Biloxi, Miss	U.S. 90
42	Biloxi, Miss	Biloxi, Miss.[2]	U.S. 90
43	Biloxi, Miss	Mobile, Ala	U.S. 90
44	Mobile, Ala	Mobile, Ala.[2]	U.S. 90
45	Mobile, Ala	Chipley, Fla	U.S. 90
46	Fort Pierce, Fla	Daytona Beach, Fla	U.S. 1
47	Daytona Beach, Fla	Daytona Beach, Fla.[2]	U.S. 1
48	Jacksonville, Fla	Jacksonville, Fla.[2]	U.S. 1, 17
49	Jacksonville, Fla	Woodbine, Ga	U.S. 17
50	Savannah, Ga	Savannah, Ga.[3]	U.S. 17
51	Hardeeville, S.C	Walterboro, S.C	U.S. 17, 17A
52	Walterboro, S.C	Summerton, S.C	U.S. 15
53	Manning, S.C	Florence, S.C	U.S. 301
54	Rowland, N.C	St. Paul, N.C	U.S. 301
55	Fayetteville, N.C	Fayetteville, N.C.[2]	U.S. 301, 401
56	Raleigh, N.C	Raleigh, N.C.[3]	U.S. 401
57	Raleigh, N.C	Norlina, N.C	U.S. 1
58	South Hill, Va	Petersburg, Va	U.S. 1
59	Petersburg, Va.[5]	Richmond, Va.[5]	U.S. 1
60	Richmond, Va.[5]	Petersburg, Va.[5]	Richmond-Petersburg Tpk.

[1] Sections 34 and 60 are toll roads.
[2] Through city, from city limit to city limit.
[3] From the center of the city to the city limit.
[4] From downtown to the residential area.
[5] For section 59, from south city limit of Petersburg to north city limit of Richmond; for section 60 the same terminals but in the opposite direction.

Table 2.—Free road and toll road comparison study sections [1]

No.	Initial point	End point	Free road route	Toll road route
1	Elizabeth, N.J	Delaware Memorial Bridge	U.S. 1, 130	New Jersey Turnpike.
18	Trenton, N.J	Delaware Memorial Bridge	U.S. 130	New Jersey Turnpike.
19	Camden, N.J	Delaware Memorial Bridge	U.S. 130	New Jersey Turnpike.
2	Syracuse, N.Y	Utica, N.Y	N.Y. 5	New York Thruway.
3	Syracuse, N.Y	Harriman, N.Y	U.S. 81, 11, 17	New York Thruway.
4	Portsmouth, N.H	Massachusetts line	U.S. 1	New Hampshire Turnpike.
51	Portland, Maine	Kittery, Maine	U.S. 1	Maine Turnpike.
6	Toledo, Ohio	Indiana line	U.S. 20	Ohio Turnpike.
7	Elkhart, Ind	Ohio line	U.S. 20	Indiana Toll Road.
8	Wichita, Kans	Wellington, Kans	U.S. 81	Kansas Turnpike.
9	Wichita, Kans	Topeka, Kans	U.S. 81, 50, 75	Kansas Turnpike.
10	Tulsa, Okla	Oklahoma City, Okla	U.S. 66	Turner Turnpike.
20	Tulsa, Okla	Miami, Okla	U.S. 66	Will Rogers Turnpike.
11	West Palm Beach, Fla	Fort Pierce, Fla	U.S. 1	Sunshine State Parkway.

[1] Three trips were made on each pair of comparison routes.

manner as closely typical of the passenger cars in the traffic stream as possible. This was done by having the vehicle "float" with the traffic; that is, operate so as to be passed by about the same number of vehicles as it overtook and passed.

During each test run the traffic impedance analyzer automatically recorded on the printer tape, once each second, the speed, distance, and time. The observer, continuously alert to traffic conditions and highway elements affecting vehicle speed, made use of the manual code box to record on the printer tape, at each speed change, a code number to identify the highway factor or traffic event causing the speed change. The left column of code numbers (on the code box and as recorded on the tape) identified highway and traffic factors such as number of lanes or whether the highway was divided or not; the right column code numbers identified traffic events such as traffic signals or a vehicle suddenly entering from a side road and causing the test vehicle to reduce speed. The complete code used was as follows:

Left column:

1. 2- or 3-lane rural; free-moving traffic.
2. 2-lane rural; trailing another vehicle and unable to pass.
3. 4- or more lane rural without access control.
4. 4- or more lane rural, divided, with access control.
5. 2- or 3-lane urban; free-moving traffic.
6. 4- or more lane urban; free-moving traffic.
7. 2- or 3-lane urban; congested traffic conditions.
8. 4- or more lane urban; congested traffic conditions.
9. 2-, 3-, or 4-lane urban, one-way; free-moving traffic conditions.
0. 2-, 3-, or 4-lane urban, one-way; congested traffic conditions.

Right column:

1. Check point.
2. Traffic signal.
3. Stop sign or flashing red signal, if stopped; otherwise, trailing a truck.
4. Sharp curve or turn, if slowed down; railroad crossing if stopped.
5. Residential driveway where entering or leaving vehicle affected the study vehicle.
6. Commercial driveway where entering or leaving vehicle affected the study vehicle.
7. Overtaking and passing maneuver by study vehicle.
8. Effect of schoolbus in rural areas; or double-parked vehicles in urban areas.
9. Vehicle turning into highway from cross road and affecting the study vehicle.
0. Blank.

The observer manually recorded on a separate data sheet the clock time, vehicle odometer reading, fuelmeter reading, and fuel temperature, at each of several check points on each test run. The check points were places where the character of the highway changed abruptly. For example, each point where a highway entered or left an urban area, even though it was only a small town, was recorded as a check point. Check points were located in this manner to make possible an analysis of the data by type of highway and character of traffic conditions. Check point locations were recorded on the printer tape by using code number 1 in the right-hand code column. Since all check points were selected in advance of the test runs, it was a relatively simple matter to go over the printer tape after completion of each run and write on the tape a complete identification of each check point. The clock time and vehicle odometer reading recorded for each check point constituted a check on the operation of the electronic measuring and recording equipment.

The numbers of access points were recorded for each study section, using hand counters. A separate count was made for cross roads and cross streets, residential driveways, and commercial driveways. Each intersecting highway or street was counted as one cross road regardless of whether it actually crossed the study route or terminated at it. All residential driveways and all entrances and exits to commercial establishments on both sides of the route, on divided as well as undivided highways, were included in the total count of access points. Where a commercial entrance was very wide, each 40 feet of width was counted as one access point. The observer counted commercial and residential driveways with two hand counters, while the vehicle operator counted cross roads with a third hand counter.

Toll route comparison sections

On each of 14 sections of the study route designated as toll route comparison sections, users desiring to travel from one end of the section to the other had a choice between using a major nontoll highway built to standards associated with roads of uncontrolled access and a toll road built to conform with the highest design standards (see table 2).

Table 3.—Average overall speeds and rates of fuel consumption of station wagon on primary routes, by type of route and number of traffic lanes

Type of route	Average overall speed in miles per hour		Average overall rate of fuel consumption			
			In gallons per mile		In miles per gallon	
	2-lane route	4-lane route	2-lane route	4-lane route	2-lane route	4-lane route
Controlled-access rural divided highways	------	60.1	------	0.09	------	11.1
Routes without controlled access:						
Rural roads [1]	49.7	47.8	0.08	.08	12.5	12.5
Main urban routes in large cities:						
Downtown areas	23.0	24.3	.08	.07	12.5	14.3
Outside downtown areas	24.9	31.1	.07	.07	14.3	14.3
Main urban routes in small towns	29.6	27.2	.07	.07	14.3	14.3

[1] Exclusive of small towns.

At each of these sections a special study was carried out to obtain directly comparable data of passenger-car operations on the toll roads and the alternate free routes. For each comparison section the termini were common to both routes. In most cases, the toll road routes included short sections of free route at each end to connect the toll routes to the free routes at the common end points.

At each toll route comparison section three test runs were made, traveling on the free road from the designated initial point to the end point and returning on the toll road. Special runs made on the New York Thruway, where the most severe terrain conditions were found, demonstrated that there was no significant difference in the toll road data by direction of travel. The operation of the vehicle on test runs and the kinds of data collected on each run were the same as described above for all test runs, except that on the toll road the electronic recording equipment was operated for only one toll road test run at each comparison section. It was not considered necessary to the conduct of the study to operate the traffic impedance analyzer to record speed changes for more than one toll road run because of the inherent uniformity of speeds encountered in toll road operations.

Analysis of Study Vehicle Data

Four separate analyses were made of the data collected: (1) A comparison of average overall speeds and rates of fuel consumption of a passenger vehicle operating on highways with the highest design standard (toll roads) as compared with operation on major thoroughfares without access control and without many of the other modern design features; (2) determination of the effect on the passenger-vehicle operation on major thoroughfares, of traffic signals, access points, and sharp curves; (3) an analysis of the relative use of toll and free routes; and (4) an investigation of the average motorist's evaluation of the time saving and improved driving comfort resulting from highway improvement.

Fuel and time consumption

The overall average speed and fuel consumption rate of the study vehicle were determined for the distance between each successive check point of each section of the study route. These were computed from the recorded elapsed time, fuel consumption, and distance data. The speeds and rates of fuel consumption computed for all portions of highway having the same general travel characteristics were then grouped together and the average values found for each group—rural divided controlled-access highways (the toll roads); and primary routes in rural areas, in urban downtown areas, in urban areas outside the downtown area, and in small towns.

The results, presented in table 3, demonstrate the general overall effects, on vehicle speeds and rates of fuel consumption, of those improvements which would consist of an increase in the number of traffic lanes from two to four, and of those improvements which bring about the upgrading of the typical primary highway of uncontrolled access to the level of routes designed to the highest standards (toll roads). The speeds and rates of fuel consumption on rural routes were about the same for both 2-lane and 4-lane roads but both were higher on toll routes as compared to free routes for the typical traffic volumes using the routes. The slightly lower average overall speed shown for 4-lane rural roads with no control of access as compared to 2-lane rural roads was undoubtedly due to the much higher traffic volumes encountered on the 4-lane roads.

On free routes in urban areas, except in small towns, the average speeds were greater on 4-lane than on 2-lane roads, but in one case the fuel consumption rates were about the same. In small towns the average overall speed was higher for 2-lane roads than for 4-lane roads, probably because of the greater frequency of traffic signal stops on 4-lane routes (see table 4). The values in table 3 provide general indications but are inconclusive for direct computation of user benefits since they do not differentiate according to traffic volumes. They are useful, however, as overall checks on time and fuel benefits computed by other means.

Effect of driveways and cross roads

The variation in the average overall speeds and fuel consumption rates of the study vehicle as related to the frequency of driveways and nonsignalized intersections (cross roads) on primary 2-lane rural roads is shown in figure 3. This figure may be used to estimate the effects on passenger-car time and fuel consumption to result through improvements reducing the frequency of access points on primary 2-lane rural roads for the ranges of average daily traffic volumes typical of such roads.

Figure 3 shows that where there were fewer than two cross roads per mile, both the average overall speed and the average rate of fuel consumption decreased with an increase in the frequency of driveways from less than 10 to 10–20 driveways per mile. However, only the average overall speed continued to decrease when the frequency of driveways was more than 20 per mile.

When the number of cross roads per mile exceeded 2, average overall speeds increased slightly with an increase in driveway frequency from less than 10 to 10–20 per mile. This slight increase reflects the circumstance that in mountainous terrain, where there are likely to be few farm entrances, road grades adversely affect vehicle speeds; while in flat or rolling terrain, where there is usually a greater frequency of farms, road grades are more conducive to higher overall speeds. It will be noted that average overall speed dropped abruptly for a driveway frequency in excess of 20 per mile.

When there were more than 2 cross roads per mile, no change in rate of fuel consumption resulted for an increase in driveway frequency from less than 10 per mile to 10–20 per mile. However, an increase in driveway frequency to over 20 per mile resulted in an appreciable reduction in fuel consumption, presumably due to the decreased speeds brought about by the increased frequency of driveways.

Traffic signals, access points, and sharp curves

Certain of the effects of traffic signals, access points, and sharp curves on passenger-car operation and the frequency of occurrence of these impedances were computed, using data collected with the traffic impedance analyzer. These are presented in table 4, differentiated according to whether the impedances were in rural or urban areas.

One important effect of a traffic impedance is to cause changes in vehicle speeds. The average number of speed change units shown in table 4 for each of the three impedances is the average for each impedance of the arithmetic sum of all speed changes associated with the movement of a vehicle past the impedance, each speed change unit being a change in speed of 1 m.p.h. For example, if a vehicle approaching a traffic signal at 50 m.p.h. slows to 25 m.p.h., increases speed to 30 m.p.h., and then slows to a stop followed later by an increase in speed back to 50 m.p.h., the total number of speed change units would be $(50-25)+(30-25)+(30-0)+(50-0)=110$ units of speed change. All single speed changes of 3 m.p.h. or less were ignored.

The percentage of traffic signals at which the study vehicle was stopped and the average duration of traffic signal stops, as well as the percentage of commercial and residential driveways at which the study vehicle was slowed by vehicles entering or leaving the traffic stream, are included in table 4 as important impedance effects for consideration in benefit studies.

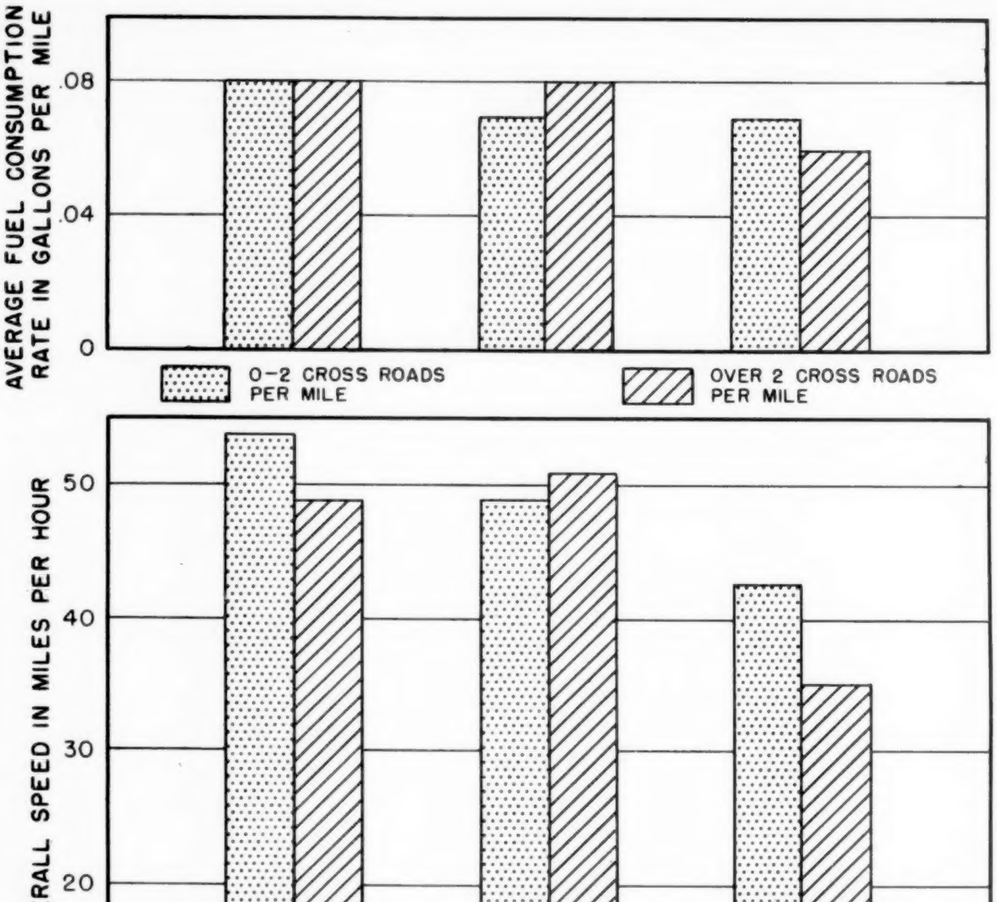

Figure 3.—Average overall speeds and fuel consumption rates on primary 2-lane rural roads as affected by frequency of driveways and cross roads.

The study vehicle was stopped by 43 percent of the traffic signals encountered in urban areas and by 30 percent of those in rural areas, with an average stopped delay of 0.29 minute and 0.21 minute in urban and rural areas, respectively.

The percentage of driveways at which the study vehicle was slowed by vehicles entering or leaving the highway at driveways was 0.5 percent (1 in 200) in urban areas and 0.8 percent (1 in 125) in rural areas. The average number of driveway access points per mile on the free routes studied was 50.2 in urban areas and 11.0 in rural areas. The average distances traveled by the study vehicle between driveways at which an entering or leaving vehicle caused a slowdown were computed, using these values, and were found to be 4 miles in urban areas and 11 miles in rural areas.

The amount of saving in fuel and time consumption that would accrue to users through the elimination of slowdowns due to driveway entrances and stops due to traffic signals can be computed using these data together with data on the fuel and time consumed by highway vehicles for stop-and-go and slowdown operations (*1*).

The usefulness to benefit studies of the speed change data shown in table 4 will be described in a later section of this article, in connection with the value to users of improved driving comfort.

Relative Use of Toll and Alternate Free Routes

Roadside interviews were conducted at stations on both the toll road and the alternate free route at each toll route comparison section on which the study vehicle was operated, to obtain information both on the relative use of the two routes and on the factors affecting user selection of one route in preference to the other. The drivers of all passenger cars operating in the direction from the initial

Table 4.—Frequency on primary highways of traffic signals, access points, and sharp curves, and their effect on operation of the study vehicle

	Urban areas	Rural areas
Average number of impedances per mile:		
Traffic signals	1.96	[1] 0.05; [1] .20
Residential driveways	16.0	5.8
Commercial driveways [2]	34.2	5.2
All driveways [2]	50.2	11.0
Cross roads	10.6	1.9
Effects of impedances on study vehicle:		
Traffic signals at which study vehicle was stopped..percent	43	30
Average stopped delay at traffic signals..minutes	.29	.21
Average number of speed change units [3] per traffic signal stop	60	90
Driveways [2] at which study vehicle was slowed by entering or leaving vehicle..percent	.5	.8
Average number of speed change units [3] per driveway [2] at which study vehicle was slowed by entering or leaving vehicle	20	20
Average number of speed change units [3] per sharp curve	15	15

[1] 0.05 for 2-lane roads; 0.20 for 4-lane roads.
[2] For wide commercial entrances, each 40 feet of width was counted as one access point.
[3] The number of speed change units for any impedance is the arithmetic sum of speed changes associated with the impedance.

point to end point of each comparison section during a 1-day interview period (8 a.m.–8 p.m.) were stopped at each interview station and asked the following questions:

1. What is the origin of this trip? (If the origin reported was the city in which the initial point of the comparison section was located, the driver was asked to give the street address.)
2. What is the destination of this trip?
3. What is the purpose of this trip?
4. Why are you using this route rather than the alternate toll/free route?

The two interview stations for each comparison section were operated by the highway department of the State in which the particular section was located, during the week that the test runs were being made.

The data obtained at the roadside interview stations at both the toll and free routes of each of the 14 toll route comparison sections were analyzed to determine the relative use of high-type roads on which a toll is levied and alternate free routes of lower design standards. Since the interview data included trip purposes and driver responses to the interview question regarding drivers' reasons for selecting whichever route they were interviewed on, it was possible to extend the analysis to show the relative importance of some of the factors influencing driver choice of route.

In computing the percentage of the drivers electing to use the toll road at each comparison section (as given in table 6), only drivers going the full length of the comparison section whose trips originated at the initial point of the particular section were included. Drivers whose trips originated beyond the origin city

Table 5.—Drivers' reasons for choice of toll road or comparable free road, by route and by purpose of trip [1]

Section No. or purpose	Number of drivers responding	Percentage of drivers using selected route for—				
		Time saving	Greater safety	Less costly	Greater comfort and convenience	All other reasons
DRIVERS ON TOLL ROADS, BY ROUTE SECTION						
1	94	66	3	1	18	12
18	65	83	2	0	9	6
19	321	71	5	0	20	4
2	281	84	5	0	4	7
3	84	71	4	0	21	4
4	3,269	82	1	(2)	11	6
51	689	78	3	0	15	4
6	4,214	81	5	2	12	0
7	154	79	5	0	8	8
11	126	76	7	0	14	3
DRIVERS ON TOLL AND FREE ROADS, BY TRIP PURPOSE						
Work:						
Toll	2,440	83	3	2	5	7
Free	2,995	25	0	16	20	39
Shop:						
Toll	118	83	4	1	6	6
Free	590	31	0	9	23	37
Vacation:						
Toll	4,784	81	4	(2)	6	9
Free	2,864	12	(2)	10	15	63
Other social or recreation:						
Toll	1,286	78	3	(2)	11	8
Free	1,497	24	(2)	11	24	41
Other:						
Toll	669	73	4	1	9	13
Free	627	32	0	14	19	35
Total:						
Toll	9,288	80	4	1	7	8
Free	8,573	21	(2)	13	19	47
Grand total	17,861	52	2	6	13	27

[1] See table 2 for routes and terminal points of comparison sections. Sections 8, 9, 10, and 20 are omitted because data analysis was incomplete.
[2] Percentage negligible.

were excluded because it was felt that these drivers were not local people and not sufficiently aware of the travel characteristics of the comparable routes to make a rational choice. Drivers whose trips originated or ended at intermediate points were excluded since, in most cases, they would have to go an appreciable distance out of their way to make use of the alternate route.

Two significant items of information useful in passenger-car user benefit studies were brought out by the interview study: The relative importance of the factors inducing passenger-car users to elect to use a free road when a toll route is available; and the effect of trip purpose on the relative importance to passenger-car users of the factors inducing them to use either toll routes or free routes.

Reasons for choice of route

The upper portion of table 5 shows for 10 of the toll route comparison sections the breakdown of the toll road user responses to the interview inquiry as to why they elected to use the toll road instead of the free road. The reasons given by all drivers responding to this inquiry were included, whether or not their trip originated at the initial point of the comparison.

The breakdown of avowed reasons for using toll roads shows that between 66 and 84 percent of the toll road users elected to use the toll route rather than the free route to save time, 1 to 7 percent for reasons of safety, 2 percent or less to save money, up to 21 percent for improved driving comfort and convenience, and up to 12 percent for other reasons. Time saving was obviously the most important single factor inducing drivers to travel on toll roads, with improved driving comfort and convenience second in importance. Greater safety appeared to be a relatively modest factor; and cost was negligible, as would be expected. These data indicate that from the passenger-car users' point of view the highway improvements which bring about the greatest benefits are those which reduce time consumption and improve driving comfort and convenience.

The lower portion of table 5 shows for the same 10 toll routes and free routes the analysis of reasons given by the drivers for electing to use the route they were interviewed on, for each of five categories of trip purpose: Work, shop, vacation, social or recreation other than vacation, and all others.

Considering the total responses, an average of 21 percent of free road users indicated that they decided to travel on the free road to save time, 19 percent made the choice for greater driving comfort and convenience, 13 percent to save money, and 47 percent for other reasons. Only a negligible number of the free road users thought travel by the free route was safer. It will be noted that the most common reasons given by free road users for using the free route were those in the category of "all others," which included less driving monotony, desire to shop or visit at points on the free route, see a particular view, and mechanical difficulty with the vehicle. It appears that on the free roads, as on the toll roads, when only factors associated with the highway itself are considered, time saving and improved driving comfort and convenience are of the greatest importance to the passenger-car user. The percentage of passenger-car users that used the free route for reasons of greater comfort and convenience was appreciably higher than the percentage of toll road users giving this reason, which may be explained by the greater frequency and wider choice of restaurants, motels, and gasoline service stations on the free routes.

Considering individual trip purposes, the toll road users indicated that the relative importance of the various reasons for using the toll road was about the same regardless of trip purpose, except that the toll road users traveling to or from work or on shopping excursions were influenced somewhat more by time saving and less by comfort and convenience than were other users. For free road users the relative importance of the reasons for using the free route were also nearly the same for all trip purposes except that most users on vacation used the free road for "other" reasons. Only a relatively small percentage of free road users on vacation used the free road either to save time or for greater driving comfort. In general these data indicate that there is no appreciable overall difference in the importance to users of the various types of benefit by trip purpose.

Motorist's Evaluation of Time Saving and Increased Driving Comfort

The data collected at the roadside interview stations and by operation of the study vehicle on the toll roads and alternate free routes at the toll route comparison sections were analyzed to obtain estimates of the value to motorists of the time saving and the greater driving comfort and convenience they expected or experienced when operating on the toll road. Drivers do not, in general, consciously assign a separate value to each of these benefits. However, since each is effective in influencing driver selection of route, each has a certain amount of attractiveness to users, which may be measured in monetary terms.

The analysis was based upon the theory that through travelers using toll roads, where a free alternate route is available, pay a premium to do so because they expect to benefit by an amount at least equal to the toll charge. The benefits received would be one or more of the following types of benefit: Reduced operating costs, reduced accident expectancy and costs, time saving, and increased driving comfort and convenience. The value of the first two of these benefits can be estimated: Operating cost saving, on the basis of the fuel consumption difference on the two routes; accident cost saving, on the basis of published accident rate and accident cost reports. The problem is to arrive at a value of the other two benefits—time saving and increased driver comfort—on the basis of estimated values of the first two benefits, and a known toll charge presumably paid to obtain these benefits.

Table 6.—Relative use of toll roads and comparable free roads; trip lengths, free road lanes, and toll road toll charges; and reduction in accident cost expectancy on toll roads

Section No. [1]	Passenger cars originating at initial point			Trip length		No. of traffic lanes on free road	Toll charge on toll road	Reduction in accident cost expectancy on toll road [2]
	Using toll road	Using free road	Percent using toll road	Toll road	Free road			
			P				R	ΔA
			Pct.	*Mi.*	*Mi.*		*Cents*	*Cents*
1	9	5	64	103.8	107.2	4	130	11.0
18	65	15	81	55.8	58.7	4	60	6.1
19	234	883	21	29.2	29.4	4	30	3.0
2	199	368	35	53.5	50.4	2	75	4.8
3	51	28	65	240.1	216.7	2	370	19.5
4	317	159	67	16.0	16.1	2	20	1.6
51	241	155	60	49.8	48.3	2	100	4.7
6	150	142	51	68.9	67.8	2	90	6.7
7	31	9	78	69.3	62.9	2	85	5.7
8	210	110	66	27.2	26.2	2	30	2.5
9	112	14	90	134.8	165.6	2	245	19.0
10	512	72	88	86.2	98.6	2	140	10.8
20	144	31	82	74.3	80.3	2	120	8.4
11	63	185	25	65.0	57.4	4	100	5.1
Total	2,338	2,176	52	------	------	------	------	----------

[1] See table 2 for routes and terminal points of comparison sections.
[2] Based on unit accident cost expectancy of 0.07 cent per vehicle-mile on toll routes and 0.17 cent on routes without access control.

A difficulty which complicated the problem of evaluating time saving and driver comfort benefits was selection of a suitable unit with which to measure driving comfort. A minute of time could be used to measure time saving but there was no similar unit for measuring improvement of driving comfort. However, it is generally recognized that uniformity of driving speed is a characteristic of good driving conditions. Most of the highway factors that cause driver annoyance such as traffic lights and sharp curves cause vehicles to change speed, frequently causing them to reduce speed to a full stop. These considerations lead to the selection of the speed change unit of 1 m.p.h., already mentioned in connection with table 4, as the unit of driving discomfort. Each speed change unit eliminated through highway improvement is therefore considered a unit of driving comfort improvement. In determining the number of units of speed change for a highway, only variations in speed where the speed change was more than 3 m.p.h. were included since variations up to about this magnitude are typical of normal driving under the best of conditions. Using speed change units as a measure of driving discomfort, the driving discomfort of a section of highway is the arithmetic sum of all speed changes on that section of road, neglecting all single speed changes of 3 m.p.h. or less. The unit value of improved driving comfort is taken in this analysis to be the value to users of each speed change unit of 1 m.p.h. saved through highway improvement.

The data obtained at each of the 14 toll route comparison sections are summarized for the analysis of the motorist's evaluation of time saving and increased driving comfort in tables 6 and 7. Since at each comparison section a series of trips were made on both the free route and toll route, all cost data are given in these tables as differences between the values for a free route trip and a toll route trip. For this purpose each free route trip was paired with a toll route trip and the value of the differences in time consumption, speed change units, and fuel cost, as well as total cost differences, are shown for these comparison trip pairs in table 7. For each comparison section there were two or three comparison trip pairs, identified by the letters A, B, and C.

Accident cost expectancy

In table 6 are presented data on the percentage of drivers electing to use the toll route, the trip lengths, both of the toll and free routes, the number of traffic lanes on the free routes, the toll charge on the toll roads, and the reduction in accident cost expectancy on the toll roads as compared with the free routes. The percentage of drivers electing to travel by toll route was determined from the interviews, using only the drivers on the compared routes whose trip origins were at the initial points of the compared sections.

The saving in accident cost expectancy for operation on the toll route as shown in table 6 is the difference in the average cost of accidents for a passenger car traversing the full length of each comparison section over the toll route as compared to operation over the free route. The accident expectancy cost of a passenger car on each route is the product of the route length in miles, the average accident rate of all types of accidents per vehicle-mile, and the average cost of a passenger-car accident. The average accident rates used in these computations were 151 accidents per 100 million vehicle-miles on toll roads and 332 accidents per 100 million vehicle-miles on roads with no access control, as reported in *The Federal Role in Highway Safety* (*5*).

The average cost of a passenger-car accident on primary rural routes with no control of access was determined as $521 per accident by a study of accident costs in Massachusetts in 1953 (*6*). Certain types of accidents that occur on such highways very seldom happen on divided controlled-access highways (such as the toll roads), including head-on collisions, head-on side-swipe collisions, and collisions with bicycles and scooters. While separate data on such accidents were not available for primary rural routes alone, unpublished information from the Massachusetts accident study showed that for primary and secondary rural highways combined the average cost of such accidents amounted to $33. Using this value as the saving in average passenger-car accident cost achieved through the elimination of the accident types mentioned as unlikely to occur on toll roads, the average cost of an accident on toll routes is derived as $521 − $33 = $488.

Cost differences

The cost differences for operating over the routes of each comparison section are given in table 7 for each comparison trip pair. The total additional cost for operation on the toll route as compared to operation on the free

Table 7.—Cost differences for operation on toll road as compared to alternate free road

Section No. and trip pairs [1]	Savings or additional costs for operating on toll road as compared to free road [2]			
	Saving in time	Saving in speed change units	Additional fuel cost	Total additional costs [3]
	ΔT	ΔD	ΔF	ΔM
Sec. 1:	*Min.*		*Cents*	*Cents*
A	61	3,410	−1.5	117.5
B	47	3,430	6.9	125.9
C	69	4,290	.9	119.9
Sec. 18:				
A	34	1,795	−6.9	47.0
B	30	2,140	1.2	55.1
C	28	2,055	1.5	55.4
Sec. 19:				
A	13	595	−2.7	24.3
B	7	355	1.8	28.8
C	5	420	2.7	29.7
Sec. 2:				
A	15	945	11.7	81.9
B	16	1,540	8.4	78.6
C	28	2,020	15.3	85.5
Sec. 3:				
A	62	4,580	105.3	455.8
B	60	4,970	99.0	449.5
Sec. 4:				
A	4	110	1.8	20.2
B	7	420	5.1	23.5
C	5	145	2.4	20.8
Sec. 51:				
A	26	1,915	21.6	116.9
B	22	1,190	16.5	111.8
C	31	1,280	18.0	113.3
Sec. 6:				
A	11	410	3.6	86.9
B	9	310	12.6	95.9
Sec. 7:				
A	0	975	38.4	117.7
B	2	865	33.0	112.3
C	3	745	45.0	124.3
Sec. 8:				
A	5	50	14.7	42.2
B	5	35	12.9	40.4
C	4	50	6.0	33.5
Sec. 9:				
A	53	1,390	50.1	276.1
B	51	945	30.6	256.6
Sec. 10:				
A	38	2,040	−7.5	121.7
B	35	1,960	−12.3	116.9
C	39	2,475	−1.5	127.7
Sec. 20:				
A	19	915	24.6	136.2
B	16	705	19.8	131.4
C	23	830	23.4	135.0
Sec. 11:				
A	2	425	52.5	147.4
B	0	475	52.2	147.1

[1] See table 2 for routes and terminal points of comparison sections. A comparison trip pair consists of one toll road trip and one free road trip.
[2] Savings in time and speed change units and additional fuel cost are for full trip length.
[3] Total additional costs $\Delta M = R + \Delta F - \Delta A$. Values for R and ΔA appear in table 6, and are identical for all trip pairs on a given route section.

route, for each comparison pair, is found by use of the formula:

$$\Delta M = R - \Delta A + \Delta F,$$

where ΔM is the additional cost of operation on the toll road, R is the toll charge on the toll road, ΔA is the reduction in accident cost expectancy for operation on the toll road (table 6), and ΔF is the additional fuel cost for operation on the toll road. The values for savings in time and speed change units, and the additional fuel costs, all reported in table 7, were derived from the data collected by the study vehicle.

Unit time and speed change values

The motorists at the initial points of each comparison section who wish to travel the full distance from the initial point to the end point of a comparison section are faced with the choice between two alternatives: (1) To use the toll road and pay the extra cost ΔM but save an amount of time, ΔT, and a number of speed change units (driving comfort), ΔD; or (2) to use the free road and put up with the additional time consumption and speed changes but save the total cost difference, ΔM. For the analysis, the percentage of drivers who elected to use the toll road at each location is represented by P, as given in table 6.

The first step undertaken in the analysis of the data to obtain estimates of t, the value the average motorist places on the saving of one minute of trip time, and s, the value of saving one unit of speed change, was the establishment of a relationship between these unknowns and the study data, ΔM, ΔT, ΔD, and r, where:

$$r = P/(100-P).$$

Equations defining a model of the relationship between these variables were presented by Nathan Cherniack at a workshop conference on economic analysis held in Washington, D.C., in September 1959 (7). The following simple equation is an adaptation of Cherniack's work appropriate to this analysis as developed by G. P. St. Clair, Director of the Bureau of Public Roads Highway Cost Allocation Study:

$$+\Delta M = -u \log r - t\Delta T - s\Delta D.$$

Mr. St. Clair's derivation of this equation is presented as an appendix to this report (see below).

The values of t and s were arrived at by substituting the values of ΔM, ΔT, ΔD, and r (the latter being derived from $P/100-P$) from tables 6 and 7, in a series of equations of the above form and solving by multiple regression. Only data for runs at study locations where the free routes are 2-lane roads were included in the equations. It was considered best not to include data for both 2-lane and 4-lane free roads in the equation for one multiple regression solution because of the differences in travel characteristics on the two types of road. Of particular concern was the fact that passing maneuvers measured by the amount of speed change represent a greater annoyance to drivers on 2-lane roads than they do on 4-lane roads. The data used in the multiple regression solution are those determined for the 27 comparison trip pairs of the 10 comparison sections where the free routes are 2-lane roads (see table 6).

The computations of the values of t and s by multiple regression analysis were made by Nathan Lieder, statistician for the Office of Research of the Bureau of Public Roads. The values of t and s, together with the confidence limits on the 95-percent level of accuracy, were found to be the following:

$t=2.365$ cents per minute ± 0.059 cent.
$s=0.048$ cent per speed change unit ± 0.062 cent.

The estimate of the motorist's evaluation of a minute of time saved is thus 2.37 cents on the basis of the data collected for this study, which agrees fairly well with the estimate recommended by the American Association of State Highway Officials, 2.58 cents per minute (3).

The estimate of the value to motorists of the elimination of one speed change unit (a 1 m.p.h. change in speed) is 0.05 cent. The variance of this estimate, ± 0.06 cent, is very high, however, and appears to indicate that driver discomfort is not fully measured by speed change units. Certain anomalies in the data and general observations of the field crew of this study also indicate that driver discomfort is greater than shown by the number of speed change units. For example, one obviously annoying traffic condition is for a motorist to have to trail a slow-moving vehicle for many miles on a 2-lane road before finding an opportunity to pass. The trailing driver, forced to travel at a slow but uniform speed, is annoyed because his speed is controlled by another driver and because he knows that to gain relief he must pass on a 2-lane road, which in itself is annoying. However, this distress is not reflected in speed change units.

It is evident, therefore, that further investigation is needed: First, to obtain more data on speed changes on route comparison sections; and second, to incorporate into the analysis of the motorist's evaluation of relief from driving annoyance, other measures (of annoyance) in addition to speed change units. In connection with the latter, further analysis is planned to exploit field data on the trailing operations of the study vehicle on 2-lane roads which were collected for this study but not contained in this report.

The value to passenger-car users of a minute of time saving (2.37 cents) is considered accurate since the average number of units of time saving (minutes) can be directly measured. The analysis thus gives an accurate distribution between the items of time saving and reduced driving annoyances of the average passenger-car user's evaluation of the sum of these two benefits. The relatively high value arrived at for each unit of speed change saving (0.048 cent) is due to the allocation of the travel discomfort benefit value among only the number of speed change units saved, when it probably should be allocated among the number of speed change units saved plus an unknown number of other discomfort units saved. To the extent that the amount of driving discomfort not measured by number of speed change units is in any way related to the number of speed change units, the product of 0.048 cent and the number of speed change units saved through highway improvement is a reasonable estimate of the value of the improved driving comfort benefit arising through the improvement. This estimate of the user's evaluation of each 1 m.p.h. speed reduction may be used to approximate driving comfort benefits arising through improvements which reduce the number of speed change units on roads similar to those for which study data were obtained, primary rural roads without control of access.

Impedance elimination values

In table 4 the average numbers of speed change units associated with three impedances—a traffic signal stop, an access point where a through vehicle is slowed by an entering or leaving vehicle, and a sharp curve—are shown for operation in rural areas. Multiplying these values by the estimate of the average motorist's evaluation of the elimination of one speed change unit, 0.048 cent, gives the following estimates of the comfort and convenience benefits users receive through the given highway improvements:

Elimination of a traffic signal stop in rural areas........................ 4.32 cents.
Elimination of a sharp curve... 0.72 cent.
Elimination of a slowdown (for a through vehicle) at an access point....... 0.96 cent.

APPENDIX

The following is a derivation of a simple equation relating time saving, saving in speed change units, and cost difference for operation on a toll road rather than a free road, and the percentage of traffic using the toll road, to user evaluations of a minute of time saving and a 1 m.p.h. reduction in amount of speed change.

Assume that the number of daily round trips that will be made from a given origin O, to a given destination D, for a given purpose, can be represented by the following equation:

$$V_{OD}=q\times V_O\times I_{Da}\times F(C) \quad (1)$$

where

q = a coefficient related to the propensity to make trips. This value is immaterial for present purposes.

V_O = number of vehicles domiciled in zone of origin.

I_{Da} = coefficient of attractiveness of the destination zone D for trips of the given purpose a. Then, if the purpose is home-to-work, this coefficient would be related to the number of employed persons in zone D.

$F(C)$ = a function of the average cost of trip, C.

The number of trips for all purposes is given by the equation:

$$V_{OD}=q\times V_O\times F(C)\times \Sigma I_n$$

where $\Sigma I_n = I_a + I_b + I_c + \ldots\ I_n$, the sum of all trip purpose coefficients.

Let the following represent the cost function:

$$F(C)=10^{-hC} \quad (2)$$

where h is a coefficient to account for the unknown effect of travel cost on driver trip decisions.

This equation can be simplified by putting $h=1$, but this presumably would reduce its generality and force it to conform to a curve that the data might not fit. Furthermore, $h=1$ lacks generality, since if base e were used, it would produce a different function.

In general this function behaves more or less as would be wished. If C is limited to positive values, as it should be, the function has its greatest value, one, when $C=0$; and thus the number of trips varies inversely with the cost. It is not a perfect function but it has the virtue of simplicity.

The equation therefore takes the form:

$$V_{OD}=q\times V_O\times \Sigma I_n\times 10^{-hC} \quad (3)$$

Alternative routes.—Equation 3 may be taken as applicable to all trips made from O to D, the cost C being taken as the average cost of the trip OD. There is, however, the problem of the distribution of the trips V_{OD} among two or more alternative routes having different trip costs. The equation will presumably hold for any one alternative, in relation to numbers of trips to *other destinations*. To assume that it holds for the distribution of trips to the same destination among alternative routes, it is necessary to say that the distribution of motorists' subjective appraisals of certain cost elements (values of time and driving comfort) is such that the distribution of trips among alternative routes between the same termini obeys the same cost function.

If we reduce the subscript OD to O or D, according to the point of origin, and take the suffix numbers 1 and 2 for two alternative routes between O and D, we may write, for trips from O to D:

$$V_{O1}=q\times V_O\times \Sigma I_D\times 10^{-hC1}$$

$$V_{O2}=q\times V_O\times \Sigma I_D\times 10^{-hC2}$$

$$r_O=\frac{V_{O1}}{V_{O2}}=\frac{10^{-hC1}}{10^{-hC2}}=10^{-h(C1-C2)}$$

It becomes at once obvious that the result would be exactly the same for trips originating at D:

$$r=r_O=r_D=10^{-h(C1-C2)}$$

$$\log r=-h(C1-C2)$$

$$\log r=-h(\Delta C)$$

$$\log r=-h(\Delta M+t\Delta T+s\Delta D) \quad (4)$$

where:

ΔM = the net sum of measured cost differences: operating cost, accident cost expectancy, and toll charge.

ΔT = time difference.

t = unit value of a minute of time saved.

ΔD = difference in speed change units.

s = unit value of a speed change unit eliminated.

$r=P/(100-P)$

P = percentage of sum of travelers on the two alternate routes who elect to use the toll road.

The signs of the terms must be watched. If the free route is designated as route 1, then ΔM is likely to be negative and ΔT and ΔD are likely to be positive because measured costs are less on the free route, while time and driving comfort costs are generally greater.

Taking $u=1/h$, then, from equation (4):

$$u\log r=-\Delta M-t\Delta T-s\Delta D;\ \text{and}$$

$$\Delta M=-u\log r-t\Delta T-s\Delta D \quad (5$$

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Moisture Content Determination by the Calcium Carbide Gas Pressure Method

BY THE DIVISION OF PHYSICAL RESEARCH
BUREAU OF PUBLIC ROADS

Reported by [1] JEROME R. BLYSTONE, ADRIAN PELZNER, and GEORGE P. STEFFENS, Highway Research Engineers

A rapid, reliable method of determining soil moisture content in the field with a simple, portable apparatus is an important need in highway engineering. A commercially made device for this purpose, which shows great promise, measures moisture content indirectly by gaging the pressure of gas generated when calcium carbide reacts with the moisture in a small soil sample. Tests of the apparatus are described in this article, which includes calibration curves for relating the gage readings to moisture content derived by the oven-drying method. Test results varied with the time of mixing of the calcium carbide and soil, and a 3-minute mixing time is recommended. Time-temperature relations of the chemical reaction were observed, but no significance in this relation with respect to moisture content was found.

Introduction

A QUICK AND ACCURATE METHOD of determining moisture contents in soil materials has long been one of the goals of soil engineers. Researchers have devoted much effort in developing gravimetric, chemical, electrical, nuclear, penetrometer, tension, and thermal methods for the determination of the moisture content of soils.[2] A chemical method using calcium carbide as a reagent is showing great promise.

The principle involved in this chemical method for moisture determination is that a given quantity of moisture will react with calcium carbide to produce a specific volume of gas (acetylene). The reaction is as follows: $CaC_2+2H_2O=Ca(OH)_2+C_2H_2$. Based on this principle, a device was developed in England that confined in a pressure vessel the gas produced from this reaction. The gas pressure is read on a gage located on one end of the pressure vessel, the gage being calibrated to read in percentage of moisture based on the wet weight of the sample.

Although the device has been used in England for several years for moisture determinations of foundry sand, it has only been used by highway engineers in the United States for about 2 years. This article describes the results of a study by the Bureau of Public Roads to determine the accuracy and usefulness in highway soil testing of a commercially manufactured "moisture tester."

Apparatus and Testing Procedure

The moisture tester is a hollow aluminum vessel having a pressure gage on one end and a cap with a clamping arrangement on the other. The manufacturer makes two sizes of moisture testers, one for a 6-gram sample and the other for a 26-gram sample. Only the larger device, having an approximate length of 14 inches, a cylinder diameter of 6 inches, and a weight of 3.7 pounds, was used in this study. This moisture tester is shown in figure 1. The tester with its auxiliary equipment—a carrying case, a tared scale for weighing the sample to be tested, a small scoop for measuring the calcium carbide, and a table to convert the moisture percentage to the dry weight basis used in soils work—is illustrated in figure 2.

[1] Presented at the 40th annual meeting of the Highway Research Board, Washington, D.C., January 1961.

[2] See *Bibliography on Methods for Determining Soil Moisture*, by M. D. Shaw and W. C. Arble, Pennsylvania State University, Engineering Research Bulletin B-78, 1959.

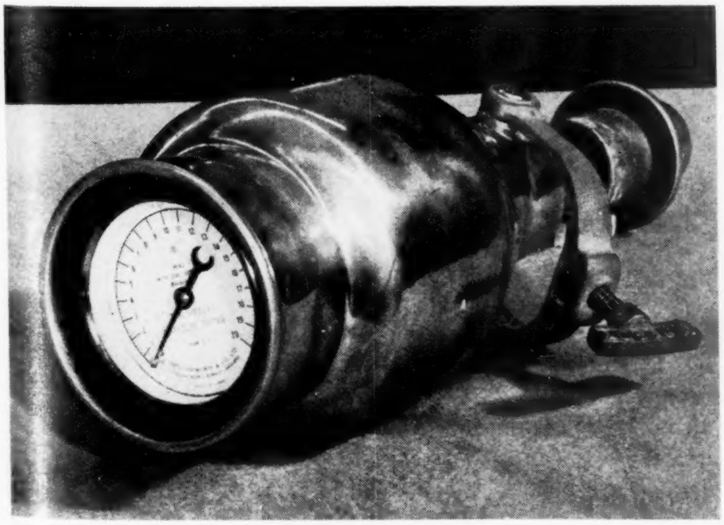

Figure 1.—Moisture tester.

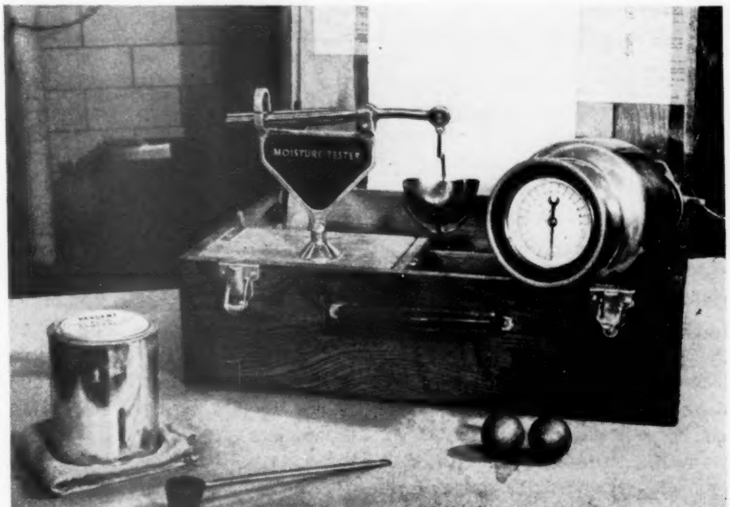

Figure 2.—Moisture tester with accessories.

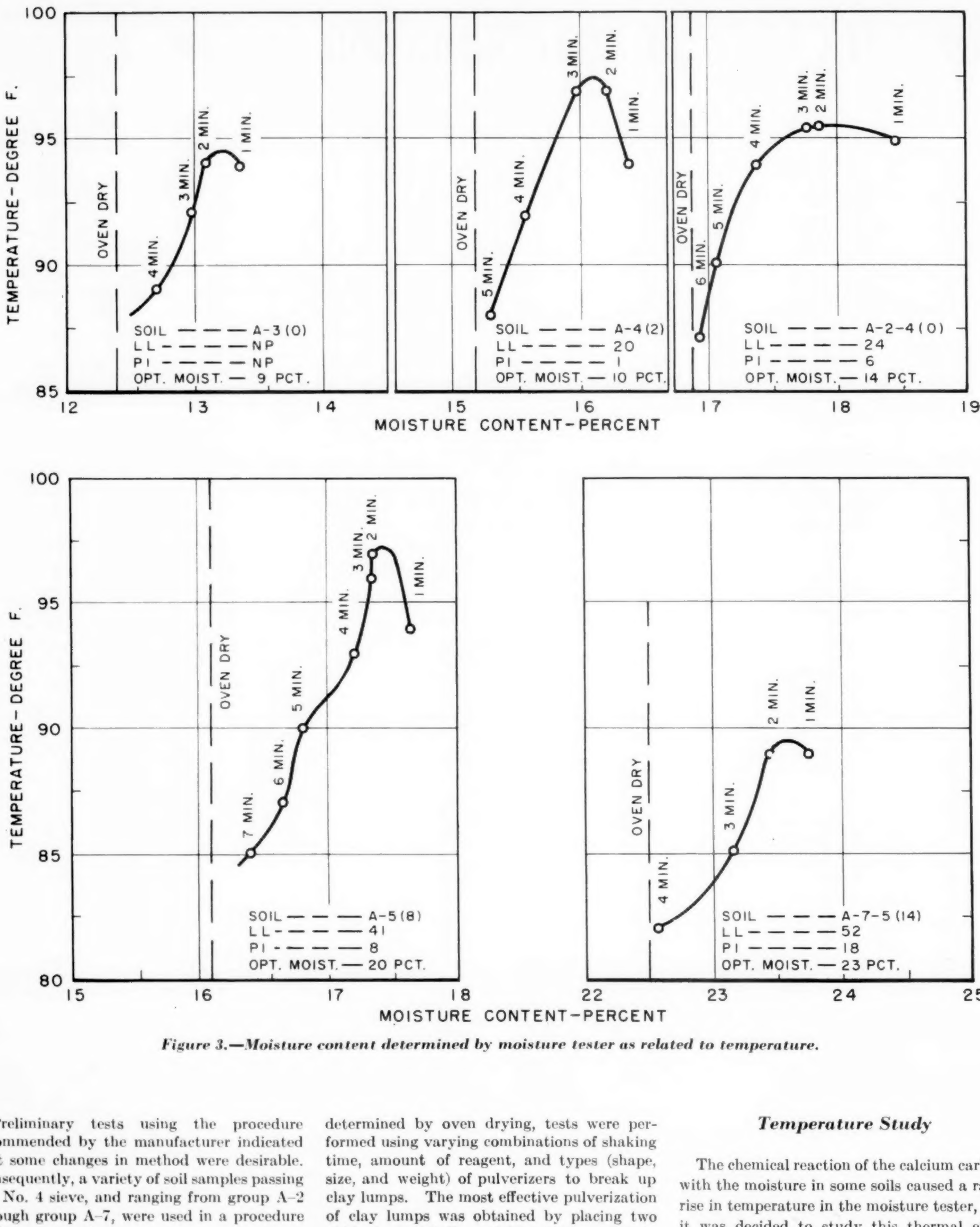

Figure 3.—Moisture content determined by moisture tester as related to temperature.

Preliminary tests using the procedure recommended by the manufacturer indicated that some changes in method were desirable. Consequently, a variety of soil samples passing the No. 4 sieve, and ranging from group A–2 through group A–7, were used in a procedure study.

The soil samples were tested at varying moisture contents in the moisture tester and by the standard oven-dry procedure. To arrive at a procedure that would give moisture contents as close as possible to those determined by oven drying, tests were performed using varying combinations of shaking time, amount of reagent, and types (shape, size, and weight) of pulverizers to break up clay lumps. The most effective pulverization of clay lumps was obtained by placing two 1¼-inch steel balls, weighing 0.4 pound each, in the moisture tester with the soil sample and calcium carbide, and agitating the device. The procedure adopted for use of the moisture tester as a result of these trials is outlined in the appendix, page 181.

Temperature Study

The chemical reaction of the calcium carbide with the moisture in some soils caused a rapid rise in temperature in the moisture tester, and it was decided to study this thermal effect more fully. An experimental program was undertaken to determine if a correlation could be established between temperature and moisture tester readings. Eleven soils, ranging from group A–2–4(0) to group A–7–5(20),

Table 1.—Physical characteristics of soils used in temperature study

AASHO soil classification	Liquid limit	Plasticity index	Optimum moisture content [1]	Range of moisture contents tested [2]
			Percent	*Percent*
A-2-4(0)	24	6	[4] 14	8.8–16.9
A-3(0)	NP [3]	NP [3]	[4] 9	4.3–15.2
A-4(2)	30	6	[4] 17	11.8–22.0
A-4(2)	20	1	10	5.8–15.2
A-4(8)	26	3	15	9.6–19.8
A-4(3)	35	9	15	11.1–22.3
A-5(8)	41	8	20	14.1–25.5
A-7-5(6)	42	11	20	15.1–28.0
A-7-5(14)	52	18	23	18.4–29.1
A-7-5(19)	66	27	27	23.8–34.4
A-7-5(20)	82	47	[4] 33	29.4–41.9

[1] AASHO Designation T 99–57, Method A.
[2] Moisture contents determined by standard oven-dry method.
[3] Nonplastic.
[4] Estimated optimum moisture content.

were selected for these tests. Their characteristics are given in table 1.

A thermometer was taped to the outer surface of the moisture tester at about the midpoint of the cylinder. Although the thermometer was insulated from external temperatures, it was recognized that the temperature recorded was not the actual temperature inside the moisture tester. However, for purposes of determining whether a correlation existed between temperature and moisture tester readings, it was not considered essential to know the actual inside temperature of the moisture tester.

After adding water to the soil, the moisture content was determined by (1) the standard oven-dry method, and (2) the moisture tester, using the procedure described in the appendix except that readings were taken at 1-minute intervals. When a soil was tested in the moisture tester, the initial temperature prior to the mixing of the soil and the calcium carbide was recorded, then the soil and chemical were mixed, and readings of the pressure gage and thermometer were recorded at 1-minute intervals until the temperature returned to within 5° F. of the initial temperature.

In this series of tests, moisture was added to the selected soil in increments of about 2 percentage points until the moisture content was past the optimum moisture content. Two successive tests were performed with the moisture tester for each increment of moisture tested. The readings of such duplicate tests were often identical or within 0.1 percentage point of each other, and most were within 0.5 percentage point of each other. The range of moisture contents tested for each soil is shown in table 1. If the moisture contents of the soils exceeded the limit of the pressure gage, half-sized samples (13 grams) were used and the percentage indicated on the gage was then doubled. There were 1,598 recordings of temperature and moisture tester readings for the selected soils in this temperature study.

The moisture tester readings were converted to a dry weight basis using the converison chart supplied by the manufacturer. For each test, diagrams of moisture content as related to temperature were plotted for 1-minute intervals until the temperature returned to within about 5 degrees of its initial value. The oven-dry moisture content was also plotted as a dashed vertical line on each diagram. Some typical diagrams are shown in figure 3.

The curves all fall to the right of the oven-dry moisture content line, indicating that the moisture contents as determined by the moisture tester were greater than as determined by oven drying. The greatest moisture content values were at the 1-minute moisture tester observations. Those moisture content determinations made from the moisture tester observations at 4, 5, and 6 minutes more nearly approach the oven-dry moisture content of the soil than those at lesser time intervals. It was anticipated that a relation might exist between the peak points of the curves and the oven-dry moisture contents, but no such relation could be determined.

Calibration Curves

The moisture content data from this temperature-moisture test program were used in developing two calibration curves for conversion of moisture tester readings to the equivalent of moisture contents obtained by oven drying. Tests covering a range of moisture contents from 4.3 to 41.9 percent were used in developing these calibration curves, shown in figure 4. The moisture tester readings at 1 minute and 3 minutes are plotted against oven-dry moisture contents. The 1-minute readings were selected for a calibration curve since the first recordings of the pressure gage of the moisture tester were taken at 1 minute. A calibration curve was developed for the 3-minute readings since this time was not considered to be excessive for running tests in the field and was adequate for the reaction of the calcium carbide to occur with moisture in clay soils. Either 13- or 26-gram samples were used in the development of the curves.

In order to establish the validity of the calibration curves and to compare the deviations using the 1- and 3-minute curves, six additional soil samples were selected for moisture testing. Each sample was tested at moisture contents bracketing the optimum (AASHO Designation T 99). The oven-dry moisture content was determined for each moisture increment added to the six soils. Using the moisture tester readings at 1 and 3 minutes and the 1- and 3-minute calibration curves (fig. 4), a predicted oven-dry moisture content was determined. These predicted values, along with the actual oven-dry values, and the deviation between them, are shown in table 2.

Table 2.—Comparison of moisture contents by moisture tester and oven drying

AASHO soil classification	Moisture content determined by—					Moisture content difference [1]	
	Dial reading on moisture tester		Calibration curves		Oven drying	1 minute	3 minute
	1 minute	3 minute	1 minute	3 minute			
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percentage point*	*Percentage point*
	5.0	5.0	5.2	5.1	5.3	0.1	0.2
A-2-4(0)	10.7	10.5	11.4	11.3	11.2	−.2	−.1
	13.8	13.8	15.1	15.4	15.7	.6	.3
	8.9	8.7	9.5	9.3	9.1	−.4	−.2
A-4(5)	12.5	12.3	13.5	13.6	13.5	.0	−.1
	18.0	17.6	20.5	20.6	20.1	−.4	−.5
	11.8	11.6	12.6	12.6	12.8	.2	.2
A-6(10)	15.2	14.9	16.7	16.8	16.5	−.2	−.3
	19.2	18.7	22.0	22.1	21.4	−.6	−.7
	14.4	14.0	15.7	15.6	15.6	−.1	.0
A-7-6(9)	18.9	18.3	21.6	21.5	20.4	−1.2	−1.1
	22.4	21.9	26.7	26.8	26.7	.0	−.1
	19.6	19.4	22.6	23.1	24.5	1.9	1.4
A-7-5(3)	23.0	22.6	27.7	28.1	28.9	1.2	.8
	27.0	26.4	34.2	34.0	35.0	.8	1.0
	22.4	22.2	26.8	27.5	29.0	2.2	1.5
A-7-5(20)	25.2	24.8	31.2	31.4	32.4	1.2	1.0
	29.6	28.8	38.5	38.0	37.9	−.6	−.1
Average deviation	--------	--------	--------	--------	--------	.7	.5

[1] Deviation of moisture content determined by moisture tester and calibration curve from oven-dry moisture content.

The moisture content values obtained from the 3-minute readings tended to be more accurate than those for 1-minute readings. For example, the A-7-5(20) soil had the greatest deviations from true moisture content, but the deviation of corrected moisture-tester values from oven-dry moisture content was 2.2 percentage points for the 1-minute reading and only 1.5 percentage points for the 3-minute reading. The average deviation for the 1-minute corrected readings was 0.7 percentage point, while the average deviation for the 3-minute corrected readings was 0.5 percentage point—only a 0.2 percentage-point difference. Nevertheless, it is recommended that the moisture tester readings be taken at the end of 3 minutes, particularly for clay samples, to ensure complete reaction of the calcium carbide with the moisture, and thus greater accuracy.

Conclusions and Applications

The moisture tester has been in use in the soils laboratory of the Bureau of Public Roads for over a year. It has proven to be a sturdy, dependable, and reasonably accurate instrument, and above all, fast and easy to operate. It is believed that by using the procedure

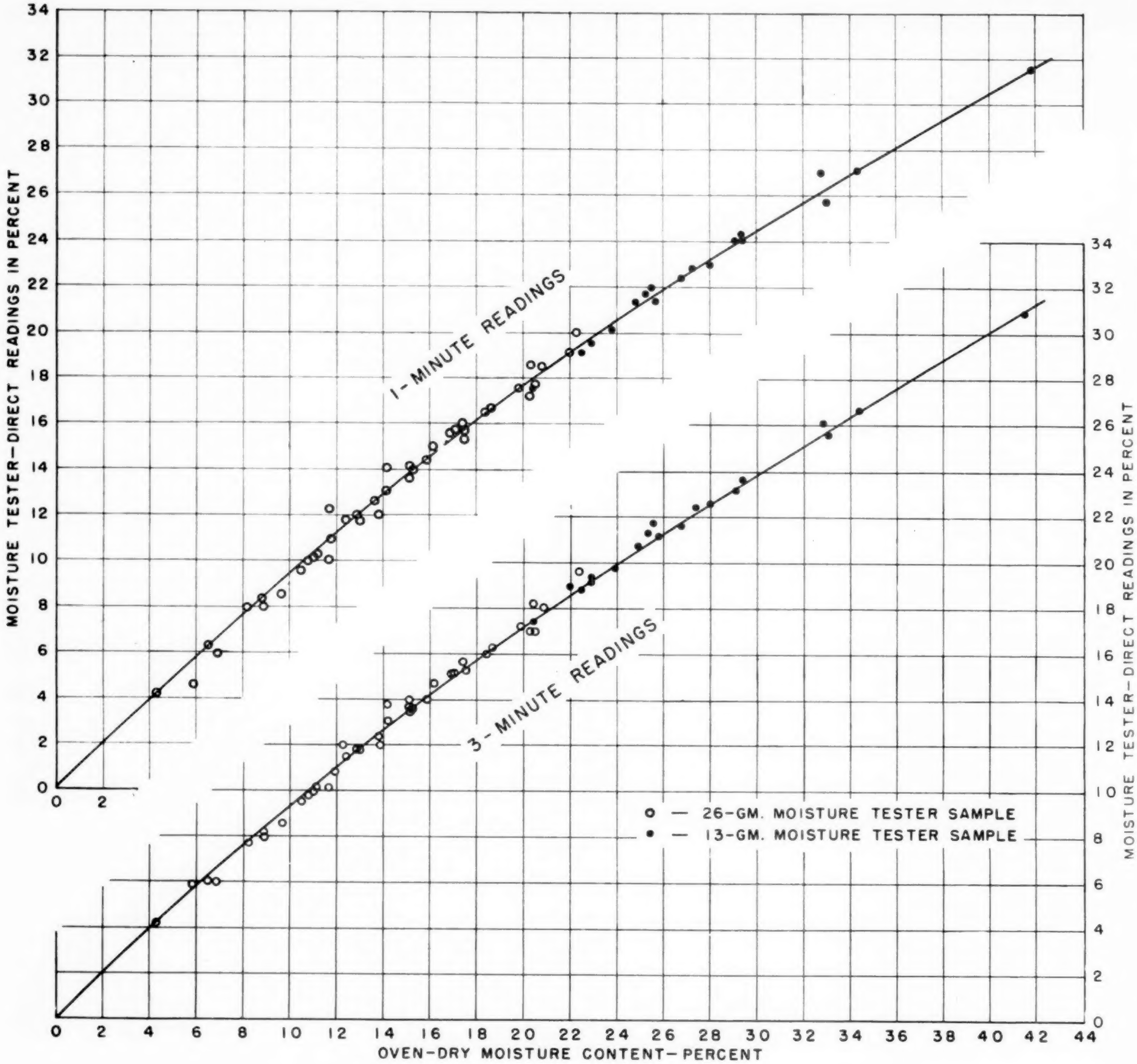

Figure 4.—Calibration curves for 1- and 3-minute moisture tester readings.

outlined in the appendix, even an inexperienced operator will become proficient in a short time. By using the 3-minute calibration curve in figure 4, direct moisture tester readings can be converted to a dry weight basis, and a moisture content value obtained that agrees closely with that obtained by oven drying.

Inasmuch as the calibration curve was developed for the specific moisture tester device tested, it is not known that the curve is applicable to each tester made by the manufacturer. Consequently, a highway department or other agency that purchases this type of moisture tester either should perform check tests with each device to determine that the calibration curve in figure 4 is applicable, or should develop a calibration curve for the specific moisture tester and local soils.

The calibration curve could be used to design a dial with values of moisture content on a dry weight basis, which would expedite moisture content determinations and eliminate possible errors in reading the calibration curve.

There are many applications of the moisture tester in highway engineering. It is well suited for the control of materials and construction practices where reasonable accuracy and rapid operations are required. The moisture tester can also be used as a quick check for field laboratory tests involving moisture content determinations. Among the possible applications of the moisture tester are the following:

Site locations.—In-place density tests; auger and split-spoon samples; sands used in concrete mixtures; and proper moisture content for earthwork.

Field laboratory.—Hygroscopic moisture; development of compaction curves; and low-value liquid and plastic limits.

Thirty-four State highway departments have reported that they have made tests with the calcium-carbide moisture tester and several are using the testers in construction control. This interest by the State highway departments appears to indicate that the calcium-carbide moisture tester is rapidly being accepted by the construction industry and the engineering profession.

Appendix—PROCEDURE FOR USE OF 26-GRAM MOISTURE TESTER [1]

1. Place three measures (approximately 22 grams) of calcium carbide and two 1¼-inch steel balls in the large chamber of the moisture tester.

2. Using the tared scale, weigh a 26-gram sample of soil.[1]

3. Place the soil sample in the cap; then, with the pressure vessel in a horizontal position, insert the cap in the pressure vessel and tighten the clamp to seal the cap to the unit.

4. Raise the moisture tester to a vertical position so the soil in the cap falls into the pressure vessel.

5. Holding the moisture tester horizontally, manually rotate the device for 10 seconds so that the steel balls are put into orbit around the inside circumference, and then rest for 20 seconds. Repeat the shake-rest cycle for a total of 3 minutes. Do not allow the steel balls to fall against either the cap or the orifice leading to the dial, since this might cause damage.

6. Read the pressure gage of the moisture tester and determine the moisture content of the soil on a dry-weight basis from the calibration curve.

[1] This procedure is for the 26-gram sized moisture tester. If the moisture content of the 26-gram soil sample exceeds the limit of the pressure gage, a half-sized sample can be used; the percentage indicated on the dial is then doubled. Since the sample to be tested is relatively small (13 or 26 grams), care must be taken to obtain a representative soil sample.

New Publications

Construction Specifications for Federal Highway Projects

The Bureau of Public Roads has recently published a new edition of *Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects.* As indicated by the title, the book is intended primarily for use in the construction of Federal road and bridge projects under the direct supervision of the Bureau. Such projects include work for which Public Roads receives direct appropriations, as for major highways through National Forests, and work performed by Public Roads for other Federal agencies.

The new publication, which for simplified reference is identified as FP–61, supersedes the 1957 edition commonly known as FP–57. Numerous changes have been made in an effort to provide up-to-date specifications for those items of work and materials and construction methods that are generally applicable to direct Federal highway contracts. As examples, thicknesses with tolerances are now to be shown for all pavement items; the use of diesel hammers is permitted for pile driving; and the radiograph method of checking welds in steel structures is recognized.

During the revision of the old specifications, the material was reviewed by both field and office engineers of the Bureau of Public Roads and by committees representing national organizations of contractors and of producers and suppliers of materials and equipment. Over a thousand different comments and suggestions were received from these sources. The benefits of these comments and suggestions are reflected in the new book.

The 371-page publication is available from the Superintendent of Documents, U.S. Government Printing Office, Washington 25, D.C., at $2.25 per copy.

The FP–61 specifications are not required or intended to be used in Federal-aid highway work performed by the States with funds administered by the Bureau of Public Roads since, as prescribed in the basic Federal-aid highway legislation, each State prepares its own specifications for Federal-aid highway construction, subject to approval by Public Roads. However, these specifications will undoubtedly be of interest to specifications writers in particular and to most engineers in highway design and construction, as well as to engineering students.

Highway Statistics, 1959

The Bureau of Public Roads has recently published *Highway Statistics, 1959,* the fifteenth in this annual series. The new bulletin presents the 1959 statistical and analytical tables of general interest on motor fuel, motor vehicles, highway-user taxation, State and local highway finance, highway mileage, and Federal aid for highways. The 153-page bulletin may be purchased from the Superintendent of Documents, Government Printing Office, Washington 25, D.C., at $1.00 per copy. Earlier annual issues of the series, and a summary of Highway Statistics to 1955, are available from the Superintendent of Documents as indicated on the inside back cover of PUBLIC ROADS.

Manual on Uniform Traffic Control Devices

The Bureau of Public Roads is receiving many requests regarding the availability of the new edition of the *Manual on Uniform Traffic Control Devices for Streets and Highways,* the preparation of which was undertaken last year. It is expected that the printing will be completed about June 30.

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